

Pionic Decay of a Possible d' -Dibaryon

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Abstract

The pionic decay of a possible d' -dibaryon in the process $d' \rightarrow N + N + \pi$ is studied in the microscopic quark shell model and with a single-quark transition operator describing the transition $q \rightarrow q + \pi$. For the d' with quantum numbers $J^P = 0^-, T = 0$, we employ a six-quark shell-model wave function with a spatial $s^5p[51]_X$ -configuration and with $N = 1$ harmonic oscillator quanta. It is shown that the pionic decay width depends strongly on the mass and size of the d' . In the case that the calculated d' mass is close to the experimental one a small pionic decay width of $\Gamma_\pi \approx 0.04$ MeV is obtained. This is an order of magnitude smaller than the experimental $\Gamma_\pi^{\text{exp}} \simeq 0.5$ MeV. Two possibilities to improve the calculated width are suggested. The effect of the nonstatic correction term in the transition operator and the influence of the form factor at the decay vertex on the decay width are also discussed.

1. INTRODUCTION

Dibaryons have a long history of more than three decades. The experimental search for dibaryons in the nucleon-nucleon (NN) channel has however not been successful yet. On the other hand, more exotic baryon-number $B = 2$ systems, that is dibaryons which have a genuine six-quark ($n(q) - n(\bar{q}) = 6$) structure that cannot be described by hadronic degrees of freedom are predicted by quantum chromodynamics (QCD). If such an exotic dibaryon is proven to exist in even a single case, the consequences would be far reaching for understanding QCD in the low-energy domain of hadron and nuclear physics [1].

Recently, new pionic double charge exchange (DCX) (π^+, π^-) data have revived the interest in dibaryon physics. DCX measurements on a number of nuclear targets ranging from ${}^4\text{He}$ to ${}^{56}\text{Fe}$ show a sharp peak in the excitation function at an incident pion energy $T_\pi \simeq 50$ MeV and at forward angles $\theta_L \approx 5^\circ$ [2, 3]. The location of the peak at $T_\pi \simeq 50$ MeV is nearly independent of the nuclear target. In the ${}^4\text{He}$ -target case, the peak appears around $T_\pi \simeq 80 - 90$ MeV [3] due to the additional 28 MeV of binding energy required to break up the ${}^4\text{He}$ nucleus into an unbound four-neutron final state.

The DCX process necessarily involves two nucleons due to charge conservation and is sensitive to short-range NN correlations. In addition, because the peak position and the width are largely independent of the target, the observed resonance-like peak is likely to be connected with some elementary process. The invariant mass spectrum of the $p + p + \pi^-$ subsystem in the $p + p \rightarrow p + p + \pi^- + \pi^+$ reaction also shows a peak at the same position as the (π^+, π^-) DCX experiments, which supports the interpretation of the observed peak as an elementary process [4].

The resonance peak, which has been called d' -dibaryon, has an energy $M_{d'} = 2065$ MeV, spin-parity $J^P = 0^-$ and isospin $T = 0$ [2]. The width of the peak is reported to be $\Gamma_{medium} \approx 5$ MeV when the effect of the Fermi motion is subtracted [2]. Such quantum numbers and such a small width are incompatible with the picture of an ordinary baryon-baryon (NN^* , N^*N^* , etc.) bound state.

Theoretically Mulders et al. predicted that six-quark states with quantum numbers $J^P = 0^-, T = 0$ should have a tetraquark (q^4) – diquark (q^2) stretched structure and a mass $M \simeq 2100$ MeV within the MIT bag model [5]. Recently, the Tübingen group has studied the microscopic structure of a possible d' -dibaryon in the nonrelativistic quark model (NRQM). Two different bases have been employed, the quark cluster model and the quark shell model [6, 7] in both cases paying due attention to the Pauli principle. In ref. [6] it has been shown that the nonrelativistic quark cluster model with a $q^4 - q^2$ -cluster configuration can account for the d' -mass of $M_{d'} \simeq 2100$ MeV if the size parameter of the d' wave function is properly chosen [6]. In the translationally invariant quark shell model (TISM) [6, 7] the six-quark states with $J^P = 0^-, T = 0$ are evaluated in a model space including $N = 1$ and $N = 3$ harmonic oscillator (h.o.) excitations. The same effective interaction potentials as in the cluster model approach are used. The quark shell model gives similar d' -masses as the quark cluster model.

Another interesting problem is whether the NRQM can explain the observed decay width of the d' -resonance. This is the objective of this article. It is reported that the major part of the observed width Γ_{medium} in DCX is due to the spreading width. The spreading width is a result of the interaction of the d' with the nucleons in the nucleus; it is absent if the d' is formed in an elementary reaction such as $p + p \rightarrow p + p + \pi^- + \pi^+$. Since the d' is not allowed to decay into the NN channel because of its quantum numbers $J^P = 0^-, T = 0$, the dominant decay mode of the d' would be the $NN\pi$ channel. The pionic decay width of the d' is estimated as small as $\Gamma_\pi \simeq 0.5$ MeV [2]. We evaluate the pionic decay width by employing the microscopic quark shell-model wave function of the d' as obtained in Ref. [7].

In contrast to the isospin-0 assumption for the d' used here, Valcarce et al. [8] have discussed the possibility that the $J^P = 0^-$ resonance in the $NN\pi$ system seen in DCX experiments is an isospin-2 resonance in the nucleon- Δ channel. Using a nonrelativistic quark model they have shown that the nucleon- Δ interaction is attractive in the $J^P = 0^-$ channel and that the decay width is explained if the calculated mass of the resonance approaches the experimental one.

This paper is organized as follows. In sect. 2 the basic expression for the pionic decay width is derived and its approximations are discussed. A refined treatment of the transition operator is also given in sect. 2. The quark shell model wave functions and the calculated d' -dibaryon mass are given in sect. 3. In sect. 4 the calculated results of the pionic decay widths are shown and the relation between the width and the d' -mass are discussed for several parameter sets. A summary is given in sect. 5.

2. PIONIC DECAY WIDTH OF THE d' -DIBARYON

2.1 Basic formula

The dominant decay mode of the d' -dibaryon with quantum numbers $J^P = 0^-, T = 0$ is the pionic decay, such as $d' \rightarrow p + p + \pi^-$, $p + n + \pi^0$ and $n + n + \pi^+$. We treat the decay operator as well as the dibaryon and final nucleon states in terms of quark degrees of freedom. The decay of the d' -dibaryon arises from the single-quark transition $q \rightarrow q + \pi$, which is depicted in Fig. 1.

Fig. 1

Fig. 1 The single-quark $q \rightarrow q + \pi$ transition process. \mathbf{p} (\mathbf{p}') denotes the initial (final) quark momentum and \mathbf{k} is the pion momentum in the final state.

The transition operator is expressed after nonrelativistic reduction as

$$\mathcal{O} = \sum_{j=1}^6 \frac{f_{\pi q}}{m_\pi} (\boldsymbol{\sigma}_j \cdot \mathbf{k}) (\boldsymbol{\tau}_j \cdot \boldsymbol{\phi}) e^{-i\mathbf{k} \cdot (\mathbf{r}_j - \mathbf{R}_{\text{CM}})} \frac{1}{\sqrt{2E_\pi (2\pi)^3}}. \quad (1)$$

Here, $f_{\pi q}$ represents the coupling constant at the $qq\pi$ -vertex, $E_\pi(m_\pi)$ the pion energy (pion mass) and $\boldsymbol{\phi}$ the isovector of the pion field. The $\boldsymbol{\sigma}(\boldsymbol{\tau})$ represent the spin (isospin) operator of a single quark.

The nucleons and the pion emitted in the d' decay $d' \rightarrow N + N + \pi$ have momenta $\mathbf{q}_1, \mathbf{q}_2$ and \mathbf{k}_π , respectively, in the C.M. frame. We define

$$\mathbf{Q} = \mathbf{q}_1 + \mathbf{q}_2, \quad \mathbf{q} = \frac{\mathbf{q}_1 - \mathbf{q}_2}{2} \quad (2)$$

where $\mathbf{Q}(\mathbf{q})$ is the total (relative) momentum of the two nucleons. Momentum and energy conservation of the decay process are expressed as

$$0 = \mathbf{q}_1 + \mathbf{q}_2 + \mathbf{k}_\pi = \mathbf{Q} + \mathbf{k}_\pi, \quad (3)$$

$$M_{d'} = 2M_N + \frac{\mathbf{Q}^2}{2(2M_N)} + \frac{\mathbf{q}^2}{M_N} + \sqrt{m_\pi^2 + \mathbf{k}_\pi^2}, \quad (4)$$

respectively, where $M_{d'}$ represents the d' -dibaryon mass.

The pionic decay width is expressed as

$$\begin{aligned} \Gamma_\pi^{\text{tot}} &= 2\pi \int d\mathbf{Q} d\mathbf{q} d\mathbf{k}_\pi \delta \left(M_{d'} - 2M_N - \frac{\mathbf{Q}^2}{2(2M_N)} - \frac{\mathbf{q}^2}{M_N} - \sqrt{m_\pi^2 + \mathbf{k}_\pi^2} \right) \\ &\times \delta(\mathbf{Q} + \mathbf{k}_\pi) \frac{1}{2J_i + 1} \sum_{M_f} \sum_{M_i} \sum_{\tau_f} \\ &\times | \langle NN | J_f M_f T_f \tau_f; \boldsymbol{\phi}_\pi | \mathcal{O} | \Psi_{d'}, J_i M_i T_i \tau_i \rangle |^2 \\ &= 2\pi \int d\mathbf{q} d\mathbf{k}_\pi \delta \left(M_{d'} - 2M_N - \frac{\mathbf{k}_\pi^2}{4M_N} - \frac{\mathbf{q}^2}{M_N} - \sqrt{m_\pi^2 + \mathbf{k}_\pi^2} \right) \end{aligned}$$

$$\begin{aligned}
& \times \frac{1}{2J_i + 1} \sum_{M_f} \sum_{M_i} \sum_{\tau_f} \\
& \times | \langle "NN" J_f M_f T_f \tau_f; \phi_\pi | \mathcal{O} | \Psi_{d'}, J_i M_i T_i \tau_i \rangle |^2
\end{aligned} \tag{5}$$

where the initial d' quantum numbers are referred to as $J_i M_i T_i \tau_i$ and " NN " refers to the final two-nucleon state with quantum numbers $J_f M_f T_f \tau_f$. To be specific we assume $J_i^P = 0^-, T_i = 0$ and $J_f^P = 0^+, T_f = 1$ due to the isovector nature (τ) of the transition operator \mathcal{O} . Then the total pionic decay width can be written as

$$\Gamma_\pi = \Gamma_{\pi^-} + \Gamma_{\pi^0} + \Gamma_{\pi^+} \tag{6}$$

and Γ_{π^-} is expressed as

$$\begin{aligned}
\Gamma_{\pi^-} &= 2\pi \int d\mathbf{q} d\mathbf{k}_\pi \delta \left(M_{d'} - 2M_N - \frac{\mathbf{k}_\pi^2}{4M_N} - \frac{\mathbf{q}^2}{M_N} - \sqrt{m_\pi^2 + \mathbf{k}_\pi^2} \right) \\
&\times | \langle "NN" J_f = 0^+, T_f = 1, \tau_f = 1; \phi_{\pi^-} | \mathcal{O} | \\
&\quad \Psi_{d'}, J_i = 0^-, T_i = 0, \tau_i = 0 \rangle |^2.
\end{aligned} \tag{7}$$

Similar expressions hold for Γ_{π^0} and Γ_{π^+} . Owing to isospin invariance, one has

$$\Gamma_{\pi^-} \equiv \Gamma_{\pi^0} \equiv \Gamma_{\pi^+} \tag{8}$$

2.2 Restriction to dominant intermediate six-quark states

The decay transition matrix element can be evaluated by inserting a complete set of six-quark states as

$$\begin{aligned}
& \langle "NN" J_f = 0^+, T_f = 1, \tau_f = 1; \phi_{\pi^-} | \mathcal{O} | \Psi_{d'}, J_i = 0^-, T_i = 0, \tau_i = 0 \rangle \\
&= \sum_n \langle "NN" J_f = 0^+, T_f = 1, \tau_f = 1 | \psi_{6q,n} \rangle \\
&\quad \times \langle \psi_{6q,n}, \phi_{\pi^-} | \mathcal{O} | \Psi_{d'}, J_i = 0^-, T_i = 0, \tau_i = 0 \rangle.
\end{aligned} \tag{9}$$

The first factor on the r.h.s. of Eq. (9) is the overlap between the antisymmetrized two-nucleon state and the intermediate six-quark state of the n -th excitation. The second factor which contains the decay dynamics connects the d' -dibaryon and the intermediate six-quark state accompanying the emitted π^- -meson wave. The quark shell model $s^5 p[51]_X$ -configuration with $N = 1$ h.o. excitation is used for $\Psi_{d'}(J = 0^-, T = 0)$.

The following arguments restrict the sum over intermediate states in Eq. (9). First, the pionic decay proceeds through a one-body operator. This means that only such six-quark configurations in which a single orbit (s or p) is changed from the initial $s^5 p$ -configuration are allowed. Second, those intermediate six-quark states which have a large overlap with asymptotic NN components (large fractional parentage factors) will give an appreciable contribution to the transition matrix element. In view of this, the two lowest-lying six-quark states are adopted as intermediate states in this work. These are the $0 \hbar\omega$ $\psi_{6q}(s^6[6]_X, J = 0^+, T = 1)$ six-quark state with $N = 0$ and the $2 \hbar\omega$ excited state $\psi_{6q}(s^4 p^2[42]_X, J = 0^+, T = 1)$ with $N = 2$. A more detailed discussion of these wave functions as well as of the d' wave function is given in sect. 3.

2.3 Nonstatic correction and form factor in the transition operator

One can go beyond the static limit of Eq. (1) and consider the next-to-leading order relativistic correction in the transition operator \mathcal{O} . The nonstatic correction term at the $qq\pi$ -vertex in Fig. 1 might be important in the present quark model description of the d' decay because the ratio of pion and quark masses is not small. The nonstatic correction of order $\mathcal{O}(\frac{m_\pi}{m_q})$ can be taken into account by modifying the momentum-dependent part of the operator \mathcal{O} of Eq. (1) as follows

$$(\boldsymbol{\sigma}_j \cdot \mathbf{k}) \rightarrow \left(\boldsymbol{\sigma}_j \cdot \left(\mathbf{k} - \frac{m_\pi}{2m_q} \frac{\mathbf{p}' + \mathbf{p}}{2} \right) \right) \quad (10)$$

where \mathbf{p} (\mathbf{p}') is the initial (final) quark momentum [9]. The quark momentum-dependent term in Eq. (10) is often referred to as the recoil correction.

Another refinement is due the finite size of the $qq\pi$ -vertex in Fig. 1. Usually, this is treated by defining a renormalized momentum-dependent coupling in place of the $f_{\pi q}$ in Eq. (1)

$$f_{\pi q} \rightarrow f_{\pi q} \cdot \left[\frac{\Lambda^2}{\Lambda^2 + \mathbf{k}^2} \right]^{1/2}, \quad (11)$$

consistently with the pion-exchange potential [10]. The cut-off mass Λ measures the extension of the core-size of the quark-pion interaction.

3. THE d' -DIBARYON MASS AND QUARK SHELL MODEL WAVE FUNCTIONS

3.1 The d' -dibaryon mass and wave function

The d' -dibaryon mass and wave functions which have been studied in Refs. [6, 7] are employed in the present calculation of the pionic decay rate of the d' . The basic ingredients and the results of Refs. [6, 7] which are essential for the present calculation are thus briefly recapitulated.

Although quark dynamics is known to be described by QCD, the many-quark system ($n(q) \geq 3$) has not been solved successfully from first principles except for calculations in the lattice gauge theory. In the low-energy domain, the nonrelativistic constituent quark model works well in accounting for the regularities of single hadron spectra.

The translationally invariant quark shell model Hamiltonian which includes the effective quark-quark interaction is written as

$$H = \sum_{i=1}^n \left(m_q + \frac{\mathbf{p}_i^2}{2m_q} \right) - \frac{\mathbf{P}^2}{n(2m_q)} + \sum_{i < j}^n V^{Conf}(\mathbf{r}_i, \mathbf{r}_j) + \sum_{i < j}^n V^{res}(\mathbf{r}_i, \mathbf{r}_j). \quad (12)$$

The confinement potential V^{Conf} is necessary; it is assumed to be linear [7] or quadratic [6] in $|\mathbf{r}| = |\mathbf{r}_i - \mathbf{r}_j|$, i.e.,

$$V^{Conf}(\mathbf{r}_i, \mathbf{r}_j) = -\frac{1}{4} \boldsymbol{\lambda}_i \cdot \boldsymbol{\lambda}_j (a_c |\mathbf{r}_i - \mathbf{r}_j| - C), \quad (13)$$

or

$$= -a'_c \boldsymbol{\lambda}_i \cdot \boldsymbol{\lambda}_j (\mathbf{r}_i - \mathbf{r}_j)^2, \quad (14)$$

where λ_i is the $SU(3)_{color}$ matrix of the i -th quark. The residual interaction V^{res} is composed of the chiral field (π and σ) potential and the one-gluon exchange potential. The former one-pion and one-sigma exchange potentials are closely related to the spontaneous breaking of chiral symmetry of QCD [11, 12]. The latter one-gluon exchange potential is responsible for the short-range part of the interaction [13]. They are expressed as

$$V^{OPEP}(\mathbf{r}_i, \mathbf{r}_j) = \frac{g_{\pi q}^2}{4\pi} \frac{1}{4m_q^2} \frac{\Lambda^2}{\Lambda^2 - m_\pi^2} (\boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j) (\boldsymbol{\sigma}_i \cdot \boldsymbol{\nabla}_r) (\boldsymbol{\sigma}_j \cdot \boldsymbol{\nabla}_r) \left(\frac{e^{-m_\pi r}}{r} - \frac{e^{-\Lambda r}}{r} \right), \quad (15)$$

$$V^{OSEP}(\mathbf{r}_i, \mathbf{r}_j) = -\frac{g_{\sigma q}^2}{4\pi} \frac{\Lambda^2}{\Lambda^2 - m_\sigma^2} \left(\frac{e^{-m_\sigma r}}{r} - \frac{e^{-\Lambda r}}{r} \right) \quad (16)$$

with

$$\frac{g_{\pi q}^2}{4\pi} = \frac{g_{\sigma q}^2}{4\pi}, \quad m_\sigma^2 \simeq (2m_q)^2 + m_\pi^2, \quad \Lambda_\pi = \Lambda_\sigma = \Lambda, \quad (17)$$

and

$$V^{OGEP}(\mathbf{r}_i, \mathbf{r}_j) = \frac{1}{4} \alpha_s \lambda_i \cdot \lambda_j \left\{ \frac{1}{r} - \frac{\pi}{m_q^2} \left(1 + \frac{2}{3} \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j \right) \delta(\mathbf{r}) \right\}, \quad (18)$$

where $\boldsymbol{\sigma}_i$ is a spin operator. The vertex form factor $(\frac{\Lambda^2}{\Lambda^2 + \mathbf{k}^2})^{1/2}$ is used in deriving Eqs. (15) and (16). The relations $g_{\pi q}^2 = f_{\pi q}^2 (\frac{2m_q}{m_\pi})^2$ and $f_{\pi q} = \frac{3}{5} f_{\pi N}$ hold, where $f_{\pi N}$ is the NN π coupling constant. The parameter sets used in this work are listed in Table I for both linear and quadratic confinement potentials. For sets 1-2 the parameters are determined by fitting the light baryon masses (N , Δ , $N^*(1535)$), and by satisfying the nucleon stability condition $\partial M_N / \partial b_N = 0$ and the approximate constraints for Λ and m_q . Parameter sets 3-5 fit the N and Δ masses but underestimate the $N^*(1535)$ mass by about 300 MeV. The latter 3 parameter sets all have a small confinement strength a_c .

Table I Quark shell model parameters and the calculated d' -dibaryon mass $M_{d'}$. The b_N and b_6 are the h.o. size parameters of the final nucleon and the d' -dibaryon wave functions, respectively. m_q is the constituent quark mass. α_s, a_c, C, a'_c and Λ are the potential parameters. Set 1-3: The values of the parameters and the corresponding d' -dibaryon masses for a linear confinement potential (Eq. (13)). Set 4-5: The values of the parameters and the corresponding d' -dibaryon masses for a quadratic confinement potential (Eq. (14)).

SET	b_N [fm]	α_s	a_c [MeV · fm ⁻¹]	C [MeV]	m_q [MeV]	Λ [fm ⁻¹]	b_6 [fm]	$M_{d'}$ [MeV]
1	0.45	0.127	462	549	338	5.07	0.59	2705
2	0.47	0.074	423	500	296	7.60	0.65	2680
3	0.60	0.816	25	-32	313	10.14	1.24	2162
SET	b_N [fm]	α_s	a'_c [MeV · fm ⁻²]		m_q [MeV]	Λ [fm ⁻¹]	b_6 [fm]	$M_{d'}$ [MeV]
4	0.595	0.958	13.97	—	313	4.20	0.78	2484
5	0.595	0.958	5.0	—	313	4.20	0.95	2112

The lowest-lying harmonic oscillator state which is compatible with d' quantum numbers $J^P = 0^-$ and $T = 0$ involves one quantum excitation $N = 1$ and is uniquely expressed as

$$\Psi_{d'}(N = 1, s^5 p[51]_X, (\lambda\mu) = (10), \quad L = 1, \quad S = 1, J = 0^-, T = 0, \\ [2211]_{CT}, [222]_C). \quad (19)$$

Here, $[...]_X$, $[...]_{CT}$ and $[...]_C$ specify the space-, color-isospin- and color- symmetry, respectively, and $(\lambda\mu)$ represents the Elliott SU(3) label of h.o. quanta. The h.o. size parameter of the $\Psi_{d'}$ wave function is b_6 . Other higher excited configurations with $N = 3$ excitations and $[42]_X$ symmetry are considered in Ref.[7]. A lower d' -mass is obtained in the configuration mixing calculation but the mixing amplitudes are small. Therefore, in the present paper, we adopt only the lowest configuration of Eq. (19) for the d' -wave function. The size parameter b_6 is determined by minimizing the d' -mass. Calculated d' -masses $M_{d'}$ and corresponding size parameters b_6 are shown in Table I. It is noticed that in the cases of weaker confinement potentials (set 3 & 5), the size parameters b_6 become large and consequently lower dibaryon masses $M_{d'}$, which are comparable with the experimental resonance energy of 2065 MeV, are obtained.

3.2 The intermediate six-quark wave functions and the final two-nucleon state

Among all possible intermediate states only the lowest two six-quark states with $J^P = 0^+, T = 1$ are adopted in Eq. (9) for the evaluation of the pionic decay width of the d' . The criteria for selecting these six-quark states have already been mentioned in sect. 2.2. The lowest two states with $N = 0$ and $N = 2$ h.o. excitations are expressed as

$$\psi_{6q,1} = \psi_{6q}(N = 0, s^6[6]_X, (\lambda\mu) = (00), \quad L = 0, \quad S = 0, J = 0^+, T = 1, \\ [222]_{CT}, [222]_C) \quad (20)$$

and

$$\psi_{6q,2} = \psi_{6q}(N = 2, s^4 p^2[42]_X, (\lambda\mu) = (20), \quad L = 0, \quad S = 0, J = 0^+, T = 1, \\ [42]_{CT}, [222]_C) \quad (21)$$

The probability amplitudes for finding the two-nucleon component in these two six-quark states (fractional parentage coefficients) are $\sqrt{1/9}$ and $-\sqrt{1/25}$, respectively [14, 15], if a common h.o. size parameter is assumed for $\psi_{6q,i} (i = 1, 2)$ and if the nucleon has an s^3 -configuration.

The final outgoing two-nucleon state is approximately written as

$$| \text{''} NN \text{''}; J = 0^+, T = 1 > \\ = \frac{1}{\sqrt{2}} | \psi_N \psi_N \frac{1}{(2\pi)^{3/2}} [e^{i\mathbf{q}\mathbf{r}} - (-1)^{S+T} e^{-i\mathbf{q}\mathbf{r}}] \chi_{M_S}^{S=0} \xi_{M_T}^{T=1}; \\ L = 0, S = 0, J = 0^+, T = 1 > \quad (22)$$

In Eq. (22), an exchange of three-quarks between nucleons is taken into account. ψ_N represents a free nucleon and its size parameter is given by b_N in Table I.

4. RESULTS AND DISCUSSION

The expression for the pionic decay width of the d' is listed in the Appendix. The analytic form of this expression is an advantage of the present model; it facilitates the discussion and interpretation of our results. The decay widths Γ_{π^-} and Γ_{π} are evaluated by adopting the wave function $\Psi_{d'}$ of Eq. (19) and several sets of parameters for the linear confinement (sets 1 – 3) and the quadratic confinement (sets 4 & 5) potential cases. The calculated decay widths are shown in Table II under the abbreviated symbols S, S+NSC and S+NSC+FF, where S refers to a calculation employing the static decay operator of Eq. (1), NSC includes the nonstatic correction term of Eq. (10), and FF refers to a calculation using the form factor of Eq. (11). In Table II, two numbers for Γ_{π^-} are listed in each column S, S+NSC and S+NSC+FF in order to show the effect of the intermediate six-quark states in Eq. (9); the numbers without parenthesis are widths evaluated by adopting both configurations $\psi_{6q,1}$ and $\psi_{6q,2}$ (abbreviated as I & II, respectively) and the numbers with parenthesis [] are the widths evaluated with configuration I only.

Table II Calculated π^- -decay width Γ_{π^-} and the total π -decay width Γ_{π} of the d' -dibaryon for the adopted parameters sets 1 - 5. The experimental data [2] is also shown. The symbol S denotes the calculation with use of the operator \mathcal{O} of Eq. (1) in the static approximation, S+NSC the calculation with the operator \mathcal{O} with inclusion of the nonstatic correction term of Eq. (10) and S+NSC+FF the calculation with the operator \mathcal{O} with inclusion of nonstatic correction term and the form factor of Eq. (11). The numbers without the parenthesis in each column of S, S+NSC and S+NSC+FF of Γ_{π^-} are the calculations when the configurations I and II ($\psi_{6q,1}$ and $\psi_{6q,2}$) are adopted for the intermediate six-quark states. The numbers with the parenthesis [] are the calculations when only the configuration I is adopted for the intermediate six-quark state. The right-most column lists the calculated decay width $\Gamma_{\pi} = 3\Gamma_{\pi^-}$.

SET	$b_6[\text{fm}]$	$M_{d'}[\text{MeV}]$	$\Gamma_{\pi^-} [\text{MeV}]$			$\Gamma_{\pi} [\text{MeV}]$
			S	S+NSC	S+NSC+FF	S+NSC+FF
1	0.59	2705	8.16 [8.83]	7.16 [7.85]	5.33 [5.82]	16.0
2	0.65	2680	6.70 [7.15]	6.34 [6.84]	5.53 [5.95]	16.6
3	1.24	2162	0.03 [0.03]	0.01 [0.02]	0.01 [0.02]	0.04
4	0.78	2484	4.22 [4.52]	3.74 [4.06]	2.90 [3.13]	8.69
5	0.95	2112	0.02 [0.02]	0.01 [0.01]	0.01 [0.01]	0.04
EXP.						$\simeq 0.5$

Let us first discuss the decay width calculated with the operator \mathcal{O} in the static approximation in Eq. (1). The calculated numbers are quoted in column S in Table II. The decay amplitude which connects the dibaryon state $\Psi_{d'}$ and the final two-nucleon and one-pion state is the essential ingredient in determining the pion decay width. The comparison of the calculated decay width with experiment provides a severe test of the validity of various model assumptions.

The pion decay width is very sensitive to the d' -dibaryon mass $M_{d'}$ which essentially determines the phase space of the three-body $NN\pi$ -decay. The decay kinematics is given in

Eqs. (3) and (4). Due to the larger phase space, a large $M_{d'}$ leads to a large pionic decay width Γ_{π^-} and Γ_{π} . This is seen in the cases of sets 1 & 2 (linear confinement) and set 4 (quadratic confinement) in Table II. If the calculated $M_{d'}$ is close to the experimental value 2065 MeV as in set 3 (linear confinement) and set 5 (quadratic confinement), a small Γ_{π^-} (Γ_{π}) is obtained.

Another factor which affects the decay width is the overlap factor between the final two-nucleon state in free space and the two three-quark-states (s^3) in the six-quark configuration. The overlap-squared is expressed as

$$\left(\frac{2(b_6/b_N)}{1 + (b_6/b_N)^2} \right)^{12}, \quad (23)$$

where $b_6(b_N)$ is the h.o. size parameter of the six-quark (free-nucleon) state. The overlap-squared values for sets 1, 2 and 4 are almost similar and as large as ≈ 0.6 , while for sets 3 & 5 the values are as small as 0.05 and 0.28, respectively. The latter small values for sets 3 & 5 are due to the very different sizes of b_6 from b_N as seen in Table I.

In view of the above two key-factors, large decay widths Γ_{π^-} are obtained for sets 1, 2 and 4, while much smaller Γ_{π^-} are obtained for sets 3 & 5 (see the column S in Table II).

One can see the role of adding the configuration II from the comparison of the two numbers without and with parenthesis []. The inclusion of configuration II reduces the decay width Γ_{π^-} by about 7 – 10 % compared with the values for configuration I only. This reduction can be physically understood. It is due to the destructive interference between the s^6 and the $s^4 p^2$ six-quark component of the NN wave function at short distances which results in a smaller intermediate six-quark amplitude [16]. The effect of the excited $N = 2$ intermediate six-quark state $\psi_{6q,2}$ with an $s^4 p^2[42]_X$ -configuration turns out to be significant but does not change the results qualitatively. This is because the transition amplitude which connects $\Psi_{d'}$ with $\psi_{6q,2}$ and ϕ_{π} is small compared with that between $\Psi_{d'}$ and $\psi_{6q,1}$ and ϕ_{π} .

We proceed to discuss the effect of the nonstatic correction (NSC) term of the transition operator to the width. Since in the preceeding paragraph the contribution of $\psi_{6q,2}$ to the amplitude is found to be rather small, we evaluate the NSC effect only for the transition from $\Psi_{d'}$ to $\psi_{6q,1}$ and ϕ_{π} .

The right-hand-side operator in Eq. (10) is rewritten as

$$\begin{aligned} (\boldsymbol{\sigma}_j \cdot \mathbf{k}) &= \left(\frac{m_{\pi}}{2m_q} \right) \frac{\boldsymbol{\sigma}_j \cdot (\mathbf{p}' + \mathbf{p})}{2} \\ &= (\boldsymbol{\sigma}_j \cdot \mathbf{k}) + \left\{ \frac{1}{2} \left(\frac{m_{\pi}}{2m_q} \right) (\boldsymbol{\sigma}_j \cdot \mathbf{k}) - \left(\frac{m_{\pi}}{2m_q} \right) (\boldsymbol{\sigma}_j \cdot \mathbf{p}) \right\}. \end{aligned} \quad (24)$$

The first term $(\boldsymbol{\sigma}_j \cdot \mathbf{k})$ is the operator in the static approximation and the second term the nonstatic correction. The transition amplitudes between $\Psi_{d'}$ and $\psi_{6q,1}$ and ϕ_{π} are expressed symbolically in the following form : For the operator $(\boldsymbol{\sigma} \cdot \mathbf{k})$ it reads

$$\langle \psi_{6q,1}, \phi_{\pi} | (\boldsymbol{\sigma} \cdot \mathbf{k}) \cdots | \Psi_{d'} \rangle \sim \text{const} \cdot (b_6 k^2) e^{-\frac{5}{24}(b_6 k)^2}, \quad (25)$$

while for the operator due to the nonstatic correction it reads

$$\begin{aligned} \langle \psi_{6q,1}, \phi_{\pi} | &\left\{ \frac{1}{2} \left(\frac{m_{\pi}}{2m_q} \right) (\boldsymbol{\sigma} \cdot \mathbf{k}) - \left(\frac{m_{\pi}}{2m_q} \right) (\boldsymbol{\sigma} \cdot \mathbf{p}) \right\} \cdots | \Psi_{d'} \rangle \\ &\sim \text{const} \cdot \left(\frac{m_{\pi}}{2m_q} \right) (\beta + \beta' (b_6 k)^2) \frac{1}{b_6} e^{-\frac{5}{24}(b_6 k)^2}, \end{aligned} \quad (26)$$

where b_6 is the size parameter of $\Psi_{d'}$ and $\psi_{6q,1}$.

Apart from the exponential factor, the following features are noticed in Eqs. (25) and (26). In the domain of large k , the term proportional to k^2 in Eq. (25) contributes most, while in the small k region the nonstatic correction dominates over the static approximation term due to the presence of the k -independent term in Eq. (26).

Combining Eqs. (25) with (26), the effect of incorporating the nonstatic correction term in the operator is written in a factorized form as [NSCI.]. An explicit expression for [NSCI.] is given in the Appendix. Note that k is replaced by k_0 in the Appendix. The factor [NSCI.] equals to 1 if no NSC is considered. The factor [NSCI.] changes appreciably as k varies. The NSC reduces the decay width Γ_{π^-} roughly by $\sim 10\%$ for sets 1, 2 and 4 compared with the corresponding values in column S. However, for set 3 the NSC is quite important and the width Γ_{π^-} is reduced to half the value in column S, while for set 5 the NSC changes Γ_{π^-} only slightly.

Finally, the form factor (FF) effect is discussed. The FF at the $qq\pi$ -vertex is of square-root type as shown in the Appendix. It is most effective for large momentum transfers k_0 . Thus a strong FF induced suppression of the decay width is seen for sets 1, 2 and 4 in which large momentum transfers k_0 are involved. On the contrary, the FF effect is negligible for sets 3 & 5 where the momentum transfer to the pion is small.

The final results for the total pionic decay width Γ_π are listed in the right-most column under the symbol S+NSC+FF, which are to be compared with the experimentally reported width $\Gamma_\pi^{\text{exp}} \simeq 0.5$ MeV. The calculated Γ_π for sets 1, 2 and 4 are too large in comparison with experiment. With $\Psi_{d'}$ and the parameters for sets 1, 2 and 4, the calculated dibaryon masses $M_{d'}$ are 600 – 400 MeV above the resonance mass 2065 MeV. This overestimation of the d' mass is mostly responsible for the large pionic decay widths. The calculated Γ_π for sets 3 & 5 are both 0.04 MeV which is an order of magnitude too small compared with the experimental data. Although the dibaryon masses $M_{d'}$ close to the experimental one are obtained by using $\Psi_{d'}$ and the parameter sets 3 and/or 5, the corresponding sizes of the dibaryon b_6 for these cases are large compared with the size parameter of the nucleon b_N . Thus the overlap factor involved in the decay width calculation comes out too small for sets 3 & 5 (0.05 & 0.28, respectively), which in turn results in a too small decay width.

We now come to a critical discussion of these results. In order to explain the pionic decay width of the d' -dibaryon, first of all the experimental d' -mass $M_{d'}$ has to be satisfactorily reproduced by the wave function $\Psi_{d'}$. With the parameters of sets 1, 2 and 4 which produce large d' -masses far from the experimental value it seems impossible to explain the decay width Γ_π^{exp} . The d' mass can be explained by $\Psi_{d'}$ with parameter sets 3 & 5. It is however noted that very weak confinement potentials are adopted for these cases and the low d' -masses $M_{d'}$ close to the experimental resonance energy are obtained at the price of having an extended radial d' wave function $\Psi_{d'}$ with a large b_6 . Thus, although the d' -mass $M_{d'}$ is correctly reproduced for sets 3 & 5, the size-parameter mismatch between the final free nucleons (b_N) and the three-quark-states (s^3) in $\Psi_{d'}$ (b_6) results in a very small overlap and consequently leads to a small pionic decay width.

Suppose that a certain Hamiltonian would produce the d' mass of 2112 MeV (set 5) with a size parameter $b_6 = 0.65$ fm (0.595 fm) in the wave function $\Psi_{d'}$. In this case one would obtain Γ_π as 0.36 MeV (0.40 MeV) which is close to the experimental $\Gamma_\pi^{\text{exp}} \simeq 0.5$ MeV.

Two possibilities are suggested to achieve a small decay width. One possibility is to study the effect of additional quark-quark interactions which are not considered in the present work and which might explain the d' mass correctly. As we have argued above, the corresponding wave function $\Psi_{d'}$ should not be much wider than the wave function of a single free baryon

in order that the overlap factor of Eq.(23) remains close to unity. The second possibility is concerned with an improved treatment of the final state. In the present work the relative motion of the final state nucleons and of the pion are simply assumed to be described by plane waves. In a more complete treatment, the final state should be calculated with the same Hamiltonian that is used to calculate the mass of the d' ; in other words an $NN\pi$ scattering wave function should be used in the calculation of the decay amplitude. If such final state wave functions are incorporated in the pionic decay process, for example in the cases of sets 3 & 5, an enhanced decay width would be obtained. This enhancement is expected because the relative wave functions are distorted and contain high momentum components which will in turn lead to an enhanced decay width [17]. It is noted that Schepkin et al. [18] have estimated the enhancement factor of the pionic decay width ($\eta \sim 5$ in their model) when they considered the final state interaction for the decaying nucleons.

5. SUMMARY

The pionic decay width of a possible d' -dibaryon found in (π^+, π^-) DCX reactions on many nuclear targets is studied in the microscopic quark shell model. We employ a single-quark transition operator which expresses the conversion of a single-quark state into another single-quark one by emitting a pion. We adopt the shell model wave functions devised by the Tübingen group. They have investigated the d' -mass and its structure in the translationally invariant quark shell model which includes the quark-quark interactions such as the confinement potential, the chiral field (π - and σ -exchange) and the one-gluon-exchange potential. In this work, the orbital d' -wave function with $J^P = 0^-, T = 0$ is given by a $s^5p[51]_X$ -configuration with $N = 1$ harmonic oscillator excitation. The pionic decay operator in its simplest form is obtained by the non-relativistic reduction of the $qq\pi$ -vertex and by imposing the static approximation on the operator. A more refined transition operator which includes the non-static (recoil) correction term and also the form factor at the $qq\pi$ -vertex is discussed.

The pionic decay transition matrix element is evaluated in our model as the sum of products of two amplitudes; the first amplitude describes the transition from the d' -state to the intermediate six-quark state and a pion, the second amplitude represents the overlap between the intermediate six-quark state and the final two-nucleon state. The sum extends over important intermediate six-quark configurations. The calculated decay width turns out to be strongly dependent on the two basic properties of the d' , i.e. its mass $M_{d'}$ and its size b_6 . The d' -dibaryon mass essentially determines the phase space of the pionic decay and hence controls the decay width. The size of d' strongly affects the overlap between the intermediate six-quark state and the final two-nucleon state. The pionic decay width also depends on the number of intermediate states included and on the treatment of the decay operator.

The pionic decay widths and masses of the d' are evaluated for microscopic d' wave functions and for several sets of model parameters [6, 7]. In the case that the calculated d' mass is 600 – 400 MeV above the experimental value 2065 MeV, the decay width $\Gamma_\pi \approx 16 - 8$ MeV is much too large compared to the experimental result. On the other hand, a decay width of $\Gamma_\pi \approx 10$ MeV is still small compared to the width of ~ 150 MeV expected for a two-body decay of the d' into the NN^* channel with subsequent pionic decay of the N^* resonance. This channel is not included in the present calculation because it is closed for the physically interesting d' masses around 2100 MeV. In the case that the d' mass is close to the experimental one, small pionic decay widths are obtained. Using the d' wave functions

and parameters of sets 3 & 5 (b_6 's are large), the calculated Γ_π 's are both 0.04 MeV which is an order of magnitude smaller than the experimental Γ_π^{exp} . We have also discussed that if one could obtain a d' mass of $\simeq 2100$ MeV with a size parameter not much different from that of a free-baryon, it would be possible to reproduce the empirical pionic decay width Γ_π^{exp} .

In this paper the role of the intermediate $s^4p^2[42]_X$ -configuration in addition to the dominant $s^6[6]_X$ -one is investigated and found to play an important role in the decay width for some parameter sets. The inclusion of the $s^4p^2[42]_X$ -configuration reduces the magnitude of the decay width compared with a calculation using only the $s^6[6]_X$ -configuration. It is also shown that the nonstatic correction in the decay operator changes the width even at low-momentum transfers and that the form factor at the decay vertex reduces the decay width for the parameter sets involving high-momentum transfers.

We conclude that the experimentally observed small pionic decay width $\Gamma_\pi^{\text{exp}} \simeq 0.5$ MeV of the d' -dibaryon can be explained by the microscopic shell model wave function and the single-quark transition operator provided that the model can reproduce the mass $M_{d'}$ correctly and the size of d' is not very different from the size of a free baryon. Finally, we find it important and necessary to go beyond the plane wave approximation and to solve the πNN final state wave function exactly within the present model in order to obtain an improved pionic decay width of the d' -dibaryon.

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Appendix

The pionic decay width of the d' -dibaryon is expressed in our model as

$$\Gamma_\pi = 3 \Gamma_{\pi^-} \quad ,$$

$$\begin{aligned} \Gamma_{\pi^-} = & \int_0^{q_{\max}} q^2 dq \frac{f_{\pi q}^2}{4\pi m_\pi^2} \frac{2M_N}{2M_N + E_\pi} \cdot 2k_0 \cdot (\text{F.F.}) \left(\frac{2(\frac{b}{b_N})}{1 + (\frac{b}{b_N})^2} \right)^{12} \\ & \times \left| \sqrt{\frac{2}{9}} \phi_{00}(q, b) \frac{10}{9} \frac{1}{\sqrt{5}} [\text{NSCI.}] b k_0^2 \exp\left[-\frac{5}{24} b^2 k_0^2\right] \right. \\ & \left. - \sqrt{\frac{2}{25}} \phi_{10}(q, b) \frac{3}{10} \frac{1}{\sqrt{10}} \left(1 - \frac{2\sqrt{3}}{9}\right) b k_0^2 \exp\left[-\frac{5}{24} b^2 k_0^2\right] \right|^2 \end{aligned}$$

where

$$(\text{F.F.}) = \frac{\Lambda^2}{\Lambda^2 + \mathbf{k}_0^2} \quad ,$$

$$\begin{aligned} [\text{NSCI.}] = & 1 + \frac{m_\pi}{2m_q} \\ & - \left(\frac{m_\pi}{2m_q} \right) \left\{ \frac{1}{2} + \frac{\ell_R(\ell_R + 1) - \ell_L(\ell_L + 1)}{2} \right\} \frac{12}{5} \frac{1}{(bk_0)^2} \\ & ; \quad (\ell_R = 1, \ell_L = 0) \quad , \end{aligned}$$

$$E_\pi = \sqrt{m_\pi^2 + k_0^2} \quad ,$$

$$\phi_{00}(q, b) = \sqrt{\frac{2^3 \sqrt{6} b^3}{\sqrt{\pi} 3^2}} \exp\left[-\frac{b^2 q^2}{3}\right] \quad ,$$

$$\phi_{10}(q, b) = \sqrt{\frac{2^2 \sqrt{6} b^3}{\sqrt{\pi} 3}} \left(1 - \frac{4}{9} b^2 q^2\right) \exp\left[-\frac{b^2 q^2}{3}\right] \quad ,$$

$$k_0 = \left[4M_N \left\{ \left(M_{d'} - \frac{q^2}{M_N}\right) - \sqrt{\left(M_{d'} - \frac{q^2}{M_N}\right)^2 - \left(M_{d'} - 2M_N - \frac{q^2}{M_N}\right)^2 + m_\pi^2} \right\} \right]^{1/2} \quad ,$$

$$q_{\max} = \sqrt{M_N(M_{d'} - 2M_N - m_\pi)} \quad .$$

In the above expression the h.o. size parameter b (b_N) denotes that of the d' -dibaryon (free nucleon). (F.F.) represents the vertex form factor and [NSCI.] the nonstatic correction effect associated with Eq. (10).

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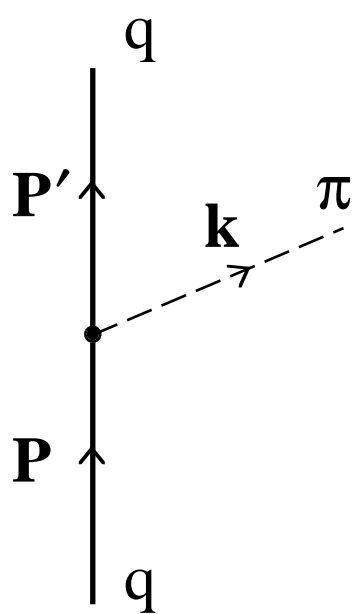


Fig. 1